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Efficacy of a Minicourse in Radiation-Reducing Techniques in Invasive Cardiology

A Multicenter Field Study

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Objectives Our goal was to validate an educational 90-min minicourse in lower-irradiating cardiac invasive techniques.

Background Despite comprehensive radiation safety programs, patient radiation exposure in invasive cardiology remains considerable.

Methods Before and at a median period of 3.7 months after the minicourse at 32 German cardiac centers, 177 interventionalists consistently documented radiation parameters for 10 coronary angiographies: dose area product (DAP), radiographic and fluoroscopic fractions, fluoroscopy time, and number of radiographic frames and runs.

Results A total of 154 cardiologists attended the minicourse and achieved significant ($p < 0.001$) decrease in patients' median overall DAP (–48.4%), from baseline 26.5 to 13.7 Gy × cm^2. They reduced fluoroscopy times (–20.8%), radiographic runs (–9.1%), frames/run (–18.6%) and frames (–29.6%), and both radiographic DAP/frame (–27.4%) and fluoroscopic DAP/s (–39.3%), which indicate improved collimation, reduced-irradiation angulations, or adequate image quality. Dose-related parameters for the remaining 23 invited cardiologists unable to attend the workshop did not change significantly in univariate comparison. Multilevel analysis ($p < 0.001$) confirmed the efficacy of the minicourse itself (–14.7 Gy × cm^2) and revealed higher DAP for increasing body mass index (+1.5 Gy × cm^2 per kg/m^2), male sex (+5.8 Gy × cm^2), age (+1.5 Gy × cm^2/decade), and—owing to different settings during image acquisition—for advanced flat-panel detector systems (+9.0 Gy × cm^2) versus older, traditional image intensifier systems.

Conclusions Despite significant required training in radiation safety for all interventional cardiologists, the presented additional 90-min minicourse significantly reduced patient dose. (J Am Coll Cardiol Intv 2014;7:382–90) © 2014 by the American College of Cardiology Foundation

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Warranted by the obvious benefits for patients, utilization of medical imaging and fluoroscopy-guided therapeutic intervention has considerably expanded throughout the world (1). Therapeutic action—particularly cardiac procedures—taken as part of this trend since 1980 has contributed to a 6-fold increase in the collective medical effective dose to the U.S. population of up to 3.0 mSv (2). Medical tests associated with the highest radiation exposure range include myocardial perfusion imaging (3), computed tomography (4), and percutaneous coronary interventions (PCIs) (5–7). Ignored for a long time by the mainstream cardiology community, the Japanese Life-Span Study supports the "linear-no-threshold" model of radiation risk, which assumes that no dose may be regarded safe or harmless (8). Over a mean follow-up period of 5 years after acute myocardial infarction, for every 10 mSv administered by cardiac imaging or fluoroscopy-guided interventions, a 3% increase in life-attributed cancer incidence was observed (9). Recent results indicate impaired cellular redox balance (10), deoxyribonucleic acid double-strand breaks (11), and radiation-induced cancer (9,12) in patients and chronically-exposed physicians. Moreover, in 3% of PCIs, the maximum skin dose exceeded the 2-Gy threshold for deterministic skin erythema (13), and owing to the complexity of the procedures, permanent skin injuries up to ulceration may result as sentinel events (6,14). To encourage acceptance, the International Atomic Energy Agency has designed its own SAFRAD (SAFety in RADiological procedures) reporting system as an independent, anonymous, and confidential registry (15). A philosophy of radiation safety, implemented in a single-center trial, recently demonstrated a 40% reduction in cumulative patient skin dose, resulting in calculated median dose area product (DAP) levels for coronary angiography (CA) and PCI of 32 and 79 Gy $\times$ cm^2, respectively (16). Despite comprehensive competence statements on the physics and safe practice of x-ray imaging, repeatedly disseminated by leading cardiovascular and radiological societies (6,14,17,18), patient radiation exposure in invasive cardiology remains considerable. According to the 2011 German National Registry (741,238 interventions at 842 catheterization laboratories), the median (mean) in-hospital DAP amounts to 23.0 (31.3) Gy $\times$ cm^2 for CA and to 50.3 (65.9) Gy $\times$ cm^2 for combined PCI (19). The corresponding effective dose confirms presently published international levels of 5 to 8 mSv for CA and 6 to 20 mSv for PCI (1,5,7,9,20). CA is evidently both a target and marker intervention for educational efforts and improved practice in radiation-reducing techniques in invasive cardiology (5,16,21,22). In conformity with widely-accepted recommendations that "all medical exposure for radiodiagnostic purposes … shall be kept *as low as reasonably achievable*" (14), we have validated effective-dose reduction techniques, focused primarily on CA, that enabled sustained mean patient DAP at low levels: that is, not only for elective CA (4.2 Gy $\times$ cm^2) (5), but also for single-vessel PCI (6.7 Gy $\times$ cm^2) and even for emergency interventions (17.3 Gy $\times$ cm^2) in acute myocardial infarction (21). Consequently, our primary objective was to investigate the efficacy of a 90-min educational, interactive, in-house program, ELICIT (Encourage Less-Irradiation Cardiac Interventional Techniques), in an expanded representative multicenter field study. The program has proved promising in clinical routine in a single-center pilot study (22).

See page 391

Methods

Definitions. Entrance skin air kerma (kinetic energy released in matter) is the dose to air in the entrance plane of the patient, also referred to as air kerma at the interventional reference point (unit: Gray [Gy]). It is independent of collimation and is used as a rough estimate of patient skin dose, which includes backscatter in the upper skin layers and represents the most appropriate quantity for characterization of deterministic skin lesions. DAP (unit: Gy $\times$ cm^2) is the product of the mean dose in air in a given plane perpendicular to the central beam and the irradiated area at this plane. It is the best-suited dose parameter for radiographic investigations with varying tube angulations. The effective dose (unit: Sievert [Sv]) is the sum of all weighted equivalent doses of exposed organs in the body and characterizes future stochastic cancer risks. Conversion factors from DAP to effective dose have been calculated at ~0.20 mSv/Gy $\times$ cm^2 for the thoracic region in adults (13).

Abbreviations and Acronyms

BMI = body mass index

CA = coronary angiography

DAP = dose area product

DAP^F = fluoroscopic dose area product

DAP^R = radiographic dose area product

IQR = interquartile range

PCI = percutaneous coronary intervention

Study design, setting, and patients. Our study design was reviewed and received approval by the local institutional ethics committee. The course program and its attendance were voluntary and free of charge. All patients and interventionalists were encoded. In accordance with the National German regulations for radiation protection, each interventionalist had completed both basic and advanced theoretical 20-h courses in radiation protection, an 8-h special course in fluoroscopic-guided interventions (required to be repeated every 5 years), and yearly mandatory fundamental 1-h refresher courses in fundamental principles of radiation protection in clinical routine. From 2003 to 2009, 177 interventional cardiologists at 32 German cardiac centers before and during a median period of 3.7 months (interquartile range [IQR]: 2.2 to 5.8 months) after the mini-course performed 10 consecutive elective CA, each by femoral access. Patients with bypass grafts or significant

JACC: CARDIOVASCULAR INTERVENTIONS, VOL. 7, NO. 4, 2014
APRIL 2014:382–90

valve diseases were excluded, because they imply a broad range of radiation doses.

Documentation included the following: total DAP; radiographic dose area product (DAP^R) and fluoroscopic dose area product (DAP^F) fractions; fluoroscopy time; and number of radiographic frames and runs. DAP^R/frame and DAP^F/s were calculated as parameters of dose intensity. A total of 26 centers used older, traditional image intensifier catheterization systems, and 6 centers employed advanced new-generation flat-panel acquisition systems (centers 11, 20 to 22, 26, and 32) (Fig. 1). Each interventionalist was instructed to use the same equipment before and after the minicourse.

Immediately prior to the minicourse, all interventionists received anonymized feedback on their individual baseline results. The interactive oral PowerPoint minicourse, a

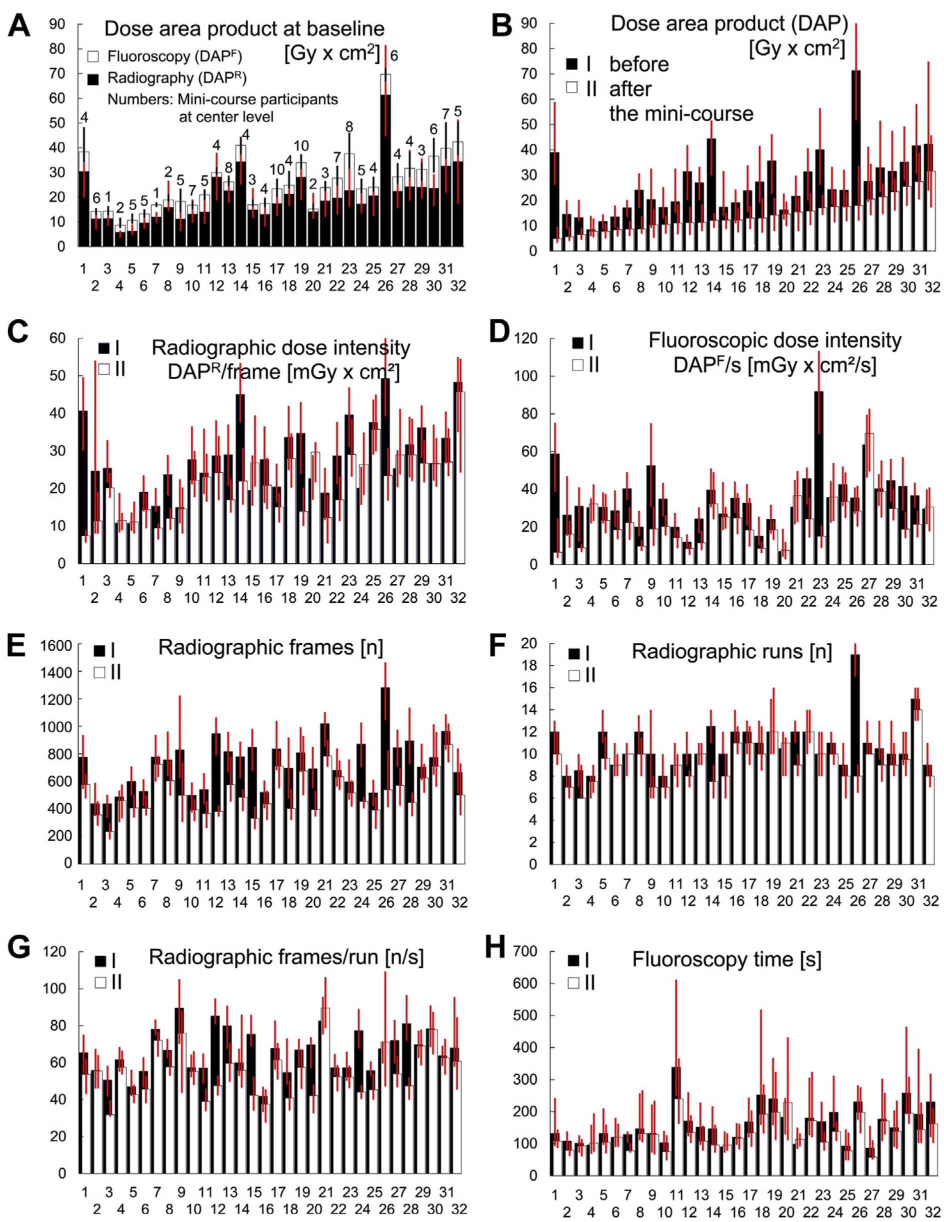

Figure 1. Results at 32 Centers for All 154 Course Participants Before and After the Minicourse

Dose area product (DAP) values at baseline and number of participating interventionalists at the respective center site **(A),** ranking **(open bars)** of median overall course efficacy **(B)** at center level from best (= 1) to less than optimal practice (= 32) after the minicourse and for a variety of specific radiation-reducing efforts assigned to the respective center sites **(C to H)**. I indicates before the minicourse; II indicates after the minicourse. DAP^F = fluoroscopic dose area product; DAP^R = radiographic dose area product.

standardized 90-min workshop, addressed the following dose-reduction principles. Each of these steps toward improved radiation safety practice was discussed in depth with published data (5,21,23) and illustrated by fluoroscopic or radiographic education videos:

- Essential radiographic runs and frames;
- Consistent collimation—fluoroscopy-free or intermittent by short pedaling—to the region of interest;
- Low-level acquisition modes during radiography and fluoroscopy: that is, copper filtering and both adequate pulse rates and detector entrance dose levels for diagnostic purposes;
- Angulations with reduced irradiation and magnification whenever possible;
- Caution taken for full inspiration during radiography;
- Long source-to-skin and short patient-to-detector distances; and
- Sufficiently well-rested operators.

A total of 154 interventionalists attended our additional voluntary workshop, conducted by 1 experienced cardiologist. Despite our intention to train as many interventionalists as possible, 23 invited cardiologists at 13 of the 32 centers could not participate due to daily duties, illness, vacation, and so on, including assumedly some colleagues who considered themselves already experienced enough in dose-optimized interventional practice. Whereas the nonparticipants obviously did not represent a valid control group, their inclusion in the analysis offered the opportunity to study a potential temporal trend that could have existed during our study program at the respective center sites from baseline evaluation until the second data capture after the conduct of our minicourse. Comparison of the group of nonparticipants with the participants, furthermore, allowed us to examine the value of any course effect within the context of pre-existing heterogeneity among operators within the centers. For this reason, we included the nonparticipants in our multilevel analysis despite the methodological shortcoming that imponderable variables involved in comparing the participants with the nonparticipants—that is, operators' experience and attitudes, interventional workload, and challenges—reduce if not negate effective analysis.

Statistical analysis. Data comparison was by the Mann-Whitney *U* test (median values and IQR of metric data) or chi-square test (categorical data) at a 2-tailed significance level of 0.05 (SAS version 9.1, SAS Institute, Cary, North Carolina). In the first step, we analyzed patient data and radiation dose parameters before and after the minicourse, with separate collection of results for operators who did and did not participate in the radiation-reduction minicourse. In the second step, we compared baseline characteristics between interventionalists with and without course participation (Table 1). We calculated Spearman correlation coefficients to describe the relation between DAP and the other radiation dose parameters for all interventions performed before and after the minicourse (Table 2). We applied the generalized linear latent and mixed models from STATA (Intercooled STATA SE version 10.1, StataCorp, College Station, Texas) to analyze in a multilevel approach the change of radiation dose parameters as a function of influencing key variables on patient (age, sex, body mass index [BMI]), operator (minicourse participation [yes, no]), and center (advanced system [yes, no]) level (Table 3). BMI data were lacking from 7 patients. Finally, a total of 3,533 complete sets of patient data have been nested in 177 interventionists, who are nested in 32 cardiac centers.

Results

The median patient overall DAP for CA performed by minicourse participants decreased significantly, from 26.5 to 13.7 Gy × cm^2—that is, by 48.4%. The concomitant reduction of DAP^R by 48.7% was a consequence of both fewer and shorter radiographic runs and of better collimation: the median number of radiographic frames decreased from 726 to 511 and the DAP^R/frame from 27.7 to 20.1 mGy × cm^2. The relative 51.9% decrease of fluoroscopic DAP^F, however, was primarily an effect of either consistently better collimation or lower dose intensity—the median DAP^F/s decreased from 33.3 to 20.2 mGy × cm^2/s—and was less the result of shorter fluoroscopy times. The remaining 23 invited cardiologists at 13 center sites who were unable to attend the minicourse started from a lower overall baseline DAP level; the achieved dose-related parameters, however, did not change significantly in univariate comparison (Table 1, nonparticipants section).

The differentiation between radiographic and fluoroscopic DAP fractions due to CA at baseline disclosed in a first step the potential of dose reduction achievable for each fraction: for example, centers 12, 15, and 20 will scarcely need further technical fluoroscopic optimization (Fig. 1A, open bars). The ranking key Figure 1B depicts the median DAP at all 32 cardiac centers before and after the minicourse and illustrates course efficacy. The centers are ranked according to lowest overall DAP after the educational program, with the ranking scale ranging from the best (= 1) to less than optimal practice (= 32). Figures 1C to 1H, for all further dose parameters, illustrate the various efforts and strategies of all 154 participating interventionalists toward radiation-reducing techniques at the center level. The interventional efforts of the 23 nonparticipants were not considered in the presented panels, because our original study design focused only on the efficacy of the completed minicourse. For the most successful center sites to the left of all panels, Figures 1C and 1D emphasize both impressively lowered dose intensities (centers 1 to 3)—owing to enhanced collimation and acceptance of adequate pulse rates

Table 1. Patients' Radiation Dose Parameters for Participants and Nonparticipants in the Minicourse in Less-Irradiating Techniques

Participants	Before Minicourse	After Minicourse	Change (%)	p Value	
Operators	154	154			
Patients	1,540	1,540			
Centers	32	32			
Patient age, yrs	65.8 (58.3–72.6)	66.1 (58.4–72.7)	+0.5	0.59	
Patient sex, female, %	34.9	36.6	+4.9	0.34	
Patient BMI, kg/m^2	27.5 (24.9–30.4)	26.8 (24.4–30.0)	–2.5	<0.001	
DAP, Gy × cm^2	26.5 (16.5–41.6)	13.7 (8.1–21.4)	–48.4	<0.001	
DAP^R, Gy × cm^2	19.7 (12.4–30.5)	10.1 (5.8–16.3)	–48.7	<0.001	
DAP^F, Gy × cm^2	5.4 (2.7–10.1)	2.6 (1.3–5.1)	–51.9	<0.001	
DAP^R/frame, mGy × cm^2	27.7 (19.2–39.4)	20.1 (12.8–29.5)	–27.4	<0.001	
DAP^F/s, mGy × cm^2/s	33.3 (21.3–48.3)	20.2 (12.0–33.0)	–39.3	<0.001	
Radiographic frames	726 (543–941)	511 (380–699)	–29.7	<0.001	
Radiographic runs	11 (9–13)	10 (8–11)	–9.1	<0.001	
Frames/run	65.5 (55–77)	53.3 (43.2–66.6)	–18.6	<0.001	
Fluoroscopy time, s	159 (102–261)	126 (84–209)	–20.8	<0.001	
Nonparticipants	**Before Minicourse**	**After Minicourse**	**Change (%)**	**p Value**	**p Value***
Operators	23	23			
Patients	230	230			
Centers	13	13			
Patient age, yrs	66.4 (57.5–74.2)	65.4 (56.3–72.5)	–1.5	0.28	0.28
Patient sex, female, %	33.9	26.1	–23.0	0.07	0.77
Patient BMI, kg/m^2	26.9 (24.1–29.9)	27.6 (25.0–29.8)	+2.6	0.11	0.02
DAP, Gy × cm^2	21.3 (15.6–29.2)	21.7 (12.9–31.4)	+1.9	0.51	<0.001
DAP^R, Gy × cm^2	16.9 (11.5–22.3)	15.6 (9.4–22.3)	–7.7	0.33	<0.001
DAP^F, Gy × cm^2	4.1 (2.2–7.4)	4.5 (2.3–9.0)	+9.8	0.24	<0.001
DAP^R/frame, mGy × cm^2	24.0 (16.3–33.3)	25.8 (17.7–36.2)	+7.5	0.09	<0.001
DAP^F/s, mGy × cm^2/s	23.7 (15.3–36.2)	22.9 (14.0–41.0)	–3.4	0.83	<0.001
Radiographic frames	691.5 (560–861)	602 (481–718)	–12.9	<0.001	0.09
Radiographic runs	10 (9–11)	10 (8–11)	0	0.14	<0.001
Frames/run	70.7 (56.7–85.3)	61.2 (50.2–76.0)	–13.4	<0.001	0.003
Fluoroscopy time, s	174 (114–264)	192 (120–280)	+10.3	0.30	0.09

Values are n or median (interquartile range). *Comparison of baseline data obtained from interventionists with and without participation (left column; upper versus lower panel) of the mini-course.
BMI = body mass index; DAP = dose area product; DAP^F = fluoroscopic dose area product; DAP^R = radiographic dose area product.

Table 2. Spearman Correlation Coefficients Between Patients' Overall DAP and Other Radiation Dose Parameters in the Cohort of 154 Participants

Parameters	Before Minicourse	After Minicourse	p Value*
DAP	1.00	1.00	
DAP^R	0.95	0.95	<0.001
DAP^F	0.76	0.71	<0.001
DAP^R/frame	0.76	0.75	<0.001
DAP^F/s	0.52	0.57	<0.001
Frames	0.61	0.54	<0.001
Radiographic runs	0.51	0.36	<0.001
Frames/run	0.32	0.37	<0.001
Fluoroscopy time, s	0.54	0.40	<0.001

Values are n. *p values for both correlation coefficients before and after the minicourse.
Abbreviations as in Table 1.

and detector entrance doses for diagnostic purposes—as well as a focus on shortened radiographic imaging (center 3) (Figs. 1E to 1G). It likewise discloses lack of radiographic copper filtering (centers 1, 14, 26, and 32) (Fig. 1C), inadequate (50/s) fluoroscopy rates (center 23) (Fig. 1D), and excessively numerous radiographic runs (center 26) (Fig. 1F). Course participants at centers, nonresponding to the minicourse, apparently perceived no reason to further improve their good practice (center 4) (Figs. 1B to 1H), or they shortened radiographic runs but neglected collimation during radiography (center 20) (Figs. 1B, 1C, and 1G). The study backmarker at baseline efficiently improved the median DAP from a "considerable" 71.3 Gy × cm^2 to an "acceptable" 18.0 Gy × cm^2, simply by introduction of recommended copper filtering during radiography and restriction to essential runs (center 26) (Figs. 1B, 1C, and 1F).

Table 3. Multilevel Analysis of All Dose Parameters Regarding Influencing Factors at Patient, Operator, and Center Level

		Patients (n = 3,533)			Operators (n = 177)		Centers (n = 32)
					Minicourse		
Influencing Factors*	Constant	BMI, kg × m^2	Age, per Decade	Sex	Participant (n = 154)	Nonparticipant (n = 23)	Advanced System (n = 6)
DAP, Gy × cm^2*	−27.4	+1.5	+1.5	+5.8	−14.7	−4.1	+9.0
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
DAP^R, Gy × cm^2	−18.0	+1.1	+0.8	+4.5	−10.7	−3.3	+9.6
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
DAP^F, Gy × cm^2	−9.1	+0.4	+0.7	+1.4	−4.1	−0.6	+0.2
p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.35	0.84
DAP^R/frame, mGy × cm^2	−20.7	+1.5	+0.8	+4.1	−6.8	−0.2	+6.5
p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.80	<0.001
DAP^F/s, mGy × cm^2/s	−27.3	+1.9	+0.8	+5.6	−12.4	−0.9	−2.5
p value	<0.001	<0.001	0.003	<0.001	<0.001	0.54	0.13
Frames	+516	+1.0	+15	+70	−208	−125	+73
p value	<0.001	0.24	<0.001	<0.001	<0.001	<0.001	<0.001
Runs	+8.3	+0.02	+0.2	+0.5	−1.5	−0.5	+1.7
p value	<0.001	0.07	<0.001	<0.001	<0.001	0.02	<0.001
Frames/run	+64.1	−0.03	−0.1	+3.3	−10.4	−8.2	+1.9
p value	<0.001	0.58	0.85	<0.001	<0.001	<0.001	0.27
Fluoroscopy time, s†	+52	+1.1	+20	+10	−55	+10	+67
p value	0.07	0.13	<0.001	0.12	<0.001	0.41	<0.001

Values are n. For the multilevel analysis: sex: 0 = female, 1 = male; for all other parameters (Participant, Nonparticipant, and Advanced System): 0 = no, 1 = yes. *Projected DAP (BMI 27.0 kg/m^2, 60 years, male), resulting from CA at an older image intensifier system: 1) before the minicourse (participant): DAP (Gy × cm^2) = −27.4 + (27 × 1.5) + (6 × 1.5) + (1 × 5.8) + (0 × −14.7) + (0 × −4.1) + (0 × 9.0) = 27.9; 2) after the minicourse (participant): DAP (Gy × cm^2) = −27.4 + (27 × 1.5) + (6 × 1.5) + (1 × 5.8) + (1 × −14.7) + (0 × −4.1) + (0 × 9.0) = 13.2. †Linear regression model: residuals of the model do not fulfill normality assumptions.

CA = coronary angiography; other abbreviations as in Table 1.

Short fluoroscopy times are evidently of secondary relevance for overall DAP (centers 1 to 32) (Figs. 1B and 1H) and are ineffective if realized at the expense of sufficient collimation (center 27) (Figs. 1D and 1H).

The best correlation with respect to overall DAP (Table 2) resulted for DAP^R, followed by DAP^F, dose intensity parameters, and number of radiographic frames. The correlation between DAP and fluoroscopy time, particularly after the minicourse, was lower.

The multilevel analysis revealed significantly ($p < 0.001$) higher DAP fractions and dose intensities with BMI, age, and male sex (Table 3): overall DAP was calculated to increase by 1.5 Gy × cm^2 per kg/m^2, 1.5 Gy × cm^2 per decade, and by 5.8 Gy × cm^2 for men. It moreover confirmed the efficacy of the minicourse itself on both DAP (−14.7 Gy × cm^2) and on all dose-influencing interventional variables. Nonparticipants at baseline achieved lower levels for radiographic DAP^R (−3.3 Gy × cm^2), fewer radiographic frames (−125), and shorter runs (−8.2 frames/run). Modern new-generation flat-panel systems with variable pulse rates were associated with higher radiographic DAP (+9.0 Gy × cm^2), more frames (+73), more runs (+1.7), more frames/run (+1.9), and higher radiographic dose intensities (+6.5 mGy × cm^2/frame).

Discussion

The interactive educational program presented here, ELICIT, an in-house 90-min minicourse, decreased DAP from CA by the considerable amount of 48.4%. This analysis represents the first validation of the efficacy of such a course in a representative multicenter field study in clinical routine. Nevertheless, great differences among the cardiac centers remained after the program: the median DAP at center level ranged between 4.9 and 31.6 Gy × cm^2. The low variances and the small interquartile ranges, however, strikingly indicate uniform interventional performance within the respective teams at most of the centers (Fig. 1).

Multilevel analysis. Our multilevel analysis revealed noteworthy details (Table 3). The positive correlation of BMI, age, and male sex with DAP fractions and dose intensities confirms our prior expectations—and reflects the necessity of more runs and longer fluoroscopy times with advancing age (which, in turn, result from the increasing complexity of expected coronary heart disease). Despite their technical radiation-reducing potential—including fluoroscopy-free collimation, heart rate adaptive selection of pulse rate, and the radiation-saving detector technology itself (24)—the advanced, new-generation catheterization systems clearly generated higher radiographic DAP.

Challenge and opportunity of advanced new-generation systems. One explanation of our findings is the significantly higher number of radiographic frames. The standard ex-works frame rate for advanced flat-panel acquisition systems is typically 15/s, compared with 12.5/s for older traditional image intensifier systems: a certain drawback that makes it more difficult to limit exposure. Because the latter acquisition rate, however, is widely accepted in daily routine—even for rapid heart rates up to ∼150/min—a radiographic frame rate of 7.5/s should consequently be adequate for diagnostic purposes up to heart rates of ∼85/min. Unfortunately, and as challenge to future safety programs, it became evident that interventionalists favor improved radiographic image resolution at the expense of higher DAP^R/frame (+6.5 mGy × cm^2/frame), over the well-recognized radiation-reducing potential of flat-panel detectors at sufficient resolution levels (Table 3).

Current guidelines and educational concepts. Pertinent international competence guidelines in radiation safety (6,14,18,25) are well accepted by the cardiology community. By now, sustained educational training concepts of the National Council on Radiation Protection and Measures (17), the International Atomic Energy Agency (26), and the MARTIR (Multimedia and Audiovisual Radiation Protection Training in Interventional Radiology) project (27) are available in material from the Internet. Evaluating the median instead of the mean values for DAP and/or fluoroscopy time, current national registries on radiation practice successfully minimize the procedure complexity of the daily challenges at different catheterization laboratories as a confounder (19). Such a benchmarking strategy could well disclose suboptimal as-low-as-reasonably-achievable practice, but cannot differentiate among the respective contributions at operator and center level. The same applies to encouraging single-center approaches toward sustained patient radiation reduction (16,28). All of these existing concepts, however, have lacked consistent documentation of relevant dose parameters that characterize the various individual radiation-reducing efforts by single cardiologists in clinical routine.

Role of comprehensive evaluation, individual training, and anonymized feedback for essential radiation dose parameters. The previously-mentioned shortcoming is resolved by the individual ELICIT approach presented here, which enables comprehensive benchmarking toward best radiation practice. Ideally, centers of excellence working in this context would participate in competence groups, with commitment to quality and safety guidelines. The educational program clearly focuses on specific reasons for suboptimal practice in individual centers: for example, with 49.3 mGy × cm^2/frame and 1,281 radiographic frames in the course of 19 diagnostic runs (center 26) (Figs. 1C, 1E, and 1F). The program likewise qualifies operators for future self-monitoring and supports an iterative improvement of their interventional technique. In general, dose-intensity parameters and the number of radiographic frames revealed the clearest correlations to patients' overall DAP, whereas the role of short fluoroscopy times (Table 2, Fig. 1H) is probably overestimated in invasive cardiology (5,21). Consistent collimation and merely adequate duration of runs proved to be effective radiation-reducing techniques and are within the reach of every interventionalist, independent of the additional radiation-reducing technical settings. Levels for DAP^R/frame and/or DAP^F/s ≥40 mGy × cm^2 disclosed inadequate technical settings: for example, lack of copper filters during radiographic acquisition at every eighth cardiac center, and unsatisfactory fluoroscopic pulse rates ≥25/s. Levels ≤20 mGy × cm^2 on the other hand, indicate adequate collimation with typical technical settings.

To take full advantage of the potential of radiation-reducing detector technology toward achieving levels ≤10 mGy × cm^2 for DAP^R/frame (centers 1 and 7) (Fig. 1C) and DAP^F/s (centers 1, 3, 8, 12, 18, and 20) (Fig. 1D), cardiac systems must, moreover, be adjusted toward promoting work with lower pulse rates, merely adequate image quality, and optimized technical installations. Implementation of such as-low-as-reasonably-achievable principles in dose evaluation and as part of operators' attitudes and daily practice is the key challenge of any radiation protection initiative and requires ongoing and unreserved cooperation of physicists and cardiologists in every catheterization laboratory.

In the minicourse described here, detailed patient exposure results achieved at baseline were pseudonymized and made accessible to interventionalists by use of their individual code numbers. This personal feedback individualized the workshop, and without risk of blame, revealed "lead foot syndrome," inadequate collimation, and suboptimal technical settings as modifiable determinants within the trainees' own areas of responsibility (29). The minicourse does not primarily intend to instruct, rather it intends to discuss established radiation safety guidelines (6,18,25) and to train under practical conditions for consistent collimation (e.g., fluoroscopic intubation into the coronary orifices by collimated "buttonhole" technique), shortened radiographic runs, merely adequate image quality, lower pulse rates, and less-irradiating angulations (5,21–23). Each step toward improved radiation safety practice was illustrated by fluoroscopic or radiographic runs. Finally, and importantly, we have learned that it is highly convincing and motivating for an interventional cardiologist to experience competitive comparison of his individual technical performance in daily routine with radiation-reducing interventional benchmarks and various strategies—as implemented by thoroughly experienced colleagues at widely-accepted cardiac centers using comparable or identical catheterization systems (Fig. 1).

Study limitations. First, although the benefits were observed only in cardiologists taking the course—and we observed no evidence for a major temporal trend in the nonparticipants—the variables involved in comparing the participants with the nonparticipants are potentially extensive and thus limit any quantitative analysis of nonparticipation as an influencing parameter. We can only speculate about the individual operators' experience, age, interventional workload, challenges, and—not least—individual willingness to change interventional practice. The fact that nonparticipants, compared with course participants, achieved lower radiographic DAP levels at baseline, fewer radiographic frames (−125), and shorter runs (−8.2 frames/run) may indicate more interventional experience (Table 3). Given the considerable extent of the observed course effect, however, it appears likely that most nonparticipants would also have enhanced their daily radiation-reduction practice had they participated.

Second, our study cannot establish the long-term efficacy of our minicourse. The 48.4% reduction of patient radiation exposure was verifiable at a median of 3.7 months (IQR: 2.2 to 5.8 months) after our workshop. Course efficacy accordingly appears unlikely to deteriorate completely in future interventional practice in the institutions involved. A single-center long-term evaluation, initiated at center 22 (Fig. 1), most recently proved a significant, long-lasting, and ongoing reduction of radiation exposure due to CA from a baseline of 31.4 Gy $\times$ cm^2 down to 15.8 Gy $\times$ cm^2 measured 2.2 months after the minicourse, and further down to 8.5 Gy $\times$ cm^2 measured 21.5 months after the course (22). However, multicenter long-term confirmation of our results in the form of sustained training (16,17) would be useful. Third, the influence of operator's individual experience was not the primary focus of this study. It remains an intriguing challenge and requires further investigations. Fourth, it would have been better if frame rates were similar across all imaging systems. It is important to note that the reason behind creation of higher patient doses compared with using traditional systems is not the advanced technology itself, but the typical settings—that is, higher frame rates and dose intensities during radiographic acquisition—in daily work at the modern flat-panel catheterization systems.

Not least, data on DAP^R/frame and DAP^F/s do not allow differentiation among the respective effects of collimation, detector entrance dose, less-irradiating angulations, or fluoroscopic pulse rates. The feedback of the overall dose intensity levels nevertheless enhanced the efficacy of our minicourse and reminded the interventionalists to optimize several of the underlying components simultaneously.

Conclusions

The ELICIT initiative presented here decreased DAP from CA by the considerable amount of 48.4% and highlighted the efficacy of practical in-house workshops in radiation protection carried out by experienced cardiologists. The benefits became apparent in overcoming ineffective radiation practice in invasive cardiology. Actual benchmarking registries (19) and encouraging single-center long-term approaches (16,28) typically evaluate merely cumulative fluoroscopy time, DAP, and/or skin dose. In an anonymous, confidential, and nevertheless individual manner, however, our course clearly focuses on the various and complex reasons for suboptimal practice (Fig. 1), indicates the main challenges, and—over the course of a few CA—qualifies operators to achieve reliable self-monitoring and iterative reduced-radiation improvements in clinical routine toward levels in the catheterization laboratory "as low as reasonably achievable" (14).

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